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NATURE-INSPIRED ACOUSTIC SENSOR PROJECTS

The following pages describe our nature-inspired, or *biomimetic*, sonars. The biological features incorporated in our sonars include:

1. Binaural reception for accurate bearing determination.
2. Wide bandwidth pulses for object recognition.
3. Echo-controlled sensor mobility.
4. Separate transmitter and receivers for sensitivity of low-level echoes from close-by objects.
5. Nonlinear signal processing for simple and fast operation.
6. Adaptive pulse repetition rate.

Sonar data are generated using custom-built electronics and conventional ultrasound transducers made by Polaroid (45 kHz PZT and 60 kHz electrostatic), Panasonic (25 kHz bimorf), Murata (40 kHz PZT bimorf), Herian Proffer (40 kHz PZT bimorf), and ITC (215 kHz PZT). Drive electronics for electrostatic transducers employ impulses or FM-chirps to maximize the bandwidth. Data are acquired with Gage analog-to-digital converters with 12 bit resolution and a sampling rate of 10 MHz. Processing is done with Pentium PCs using programs written in C or using MATLAB.

The sonars are used in a variety of sensor driven applications, including robotics and autonomous vehicles.References are provided for each system (if available).

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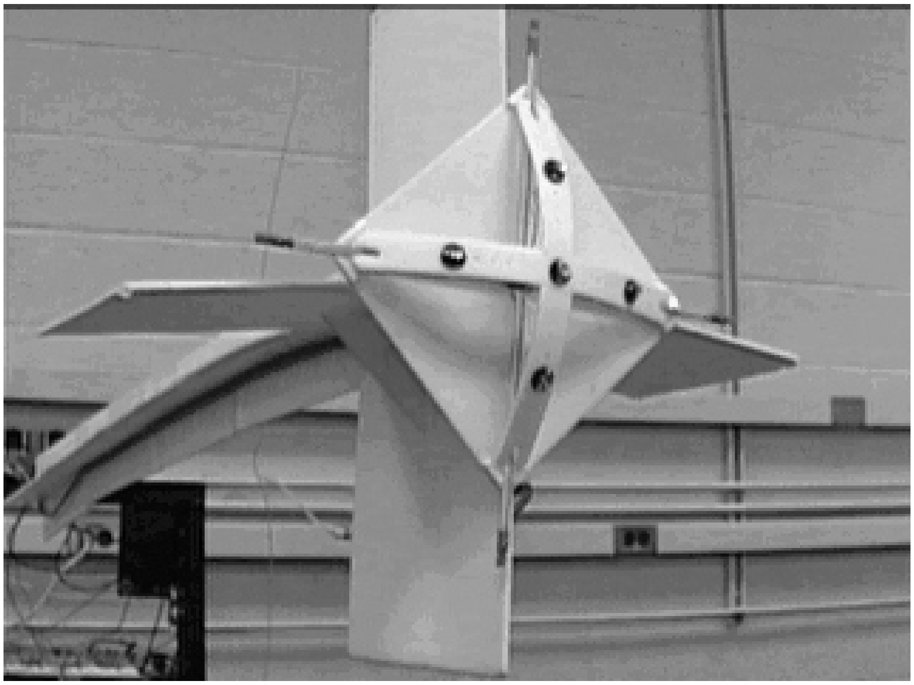
3D qualitative tracking sonar



Five 40 kHz Murata transducers are configured as a center transmitter flanked by a pair of receivers lying along the horizontal axis and a pair of receivers lying along the vertical axis. Interrogation pulses are transmitted every 10 ms. Simple logic determines which receiver in each pair detects an echo first. For example, if the top receiver detects an echo before the bottom receiver, the object must lie above the sensor horizon. A solenoid then activates a downward-directed air jet to move the sensor upward. A similar operation occurs for the left/right determination. A moving object traveling less than $\pi/2$ radians/second relative to the sensor is tracked by the sonar.

This sensor is nonlinear in sensing and control, resulting in a limit cycle about the bearing and elevation of the object. Damping fins make the mechanical system response behave as a first-order system and simplify the control of the sensor.

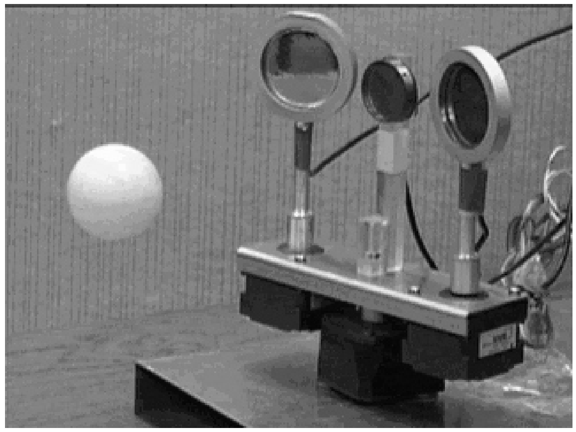
The determination of object location is made qualitatively, by identifying first arrival echoes. Hence, no triangulation computations are performed. Advantages of this approach include:

1. The sonar works over the union of the transmitter/receiver echo detection regions, which is larger than the intersection required for triangulation. Triangulation methods require that two transducers detect echoes and, hence, operate only over the intersection of the transmitter/receiver regions.

2. The sonar reacts with the arrival of the first echo, the arrival of the echo to the other receiver in the pair being irrelevant.Since the sensor does not need to wait for the other echo, correction occurs as fast as possible.

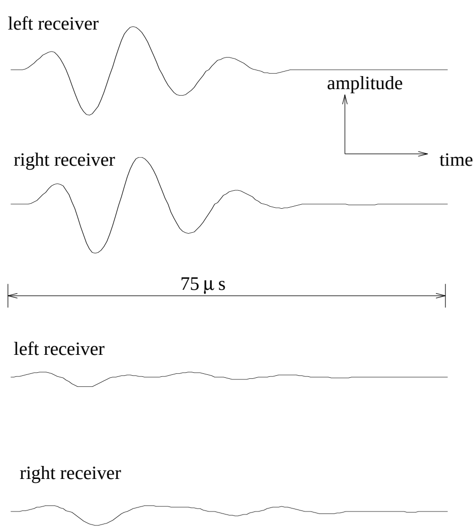
Reference: R. Kuc. Three-dimensional tracking using qualitative bionic sonar. Robotics and Autonomous Systems, 11, 213-219, 1993.

Robat – Robot bat



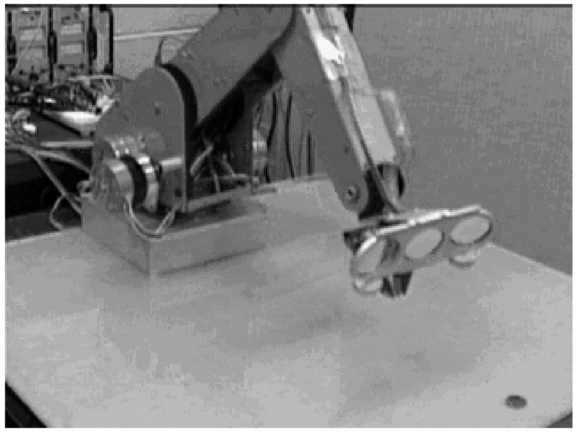
An active sonar system adaptively changes its configuration in response to the echoes it observes. The system mimics biological sonar systems in that there is a movable center transmitter (Polaroid 7000 series - 60 kHz) flanked by two adjustable receivers (Polaroid Instrumentation grade - 60 kHz). The sensor scans the environment by repeatedly performing a wide sector scan. When echoes are received, the sonar rotates to position the object along the transmitter axis to maximize the incident acoustic intensity. The receivers rotate and position the object along their axes to maximize the detected echo amplitude and bandwidth. This adapting configuration standardizes the location of the object within the beam patterns, making object recognition from echo waveforms feasible.

Pulses are transmitted every 10 ms. The sonar is capable of tracking a pendulum consisting of a ping-pong ball suspended on an 20 cm thread. Sensor rotation and receiver angle correction track the moving ball. Echo waveforms at the two receivers are shown below. The top pair shows the waveforms when the receivers are focussed on the ball. The bottom waveform pair is observed when there is no focus adjustment, i.e., the receiver axes are parallel to the transmitter axis. The increased amplitude is apparent, There is also an increase in the echo bandwidth, which aids in object recognition.

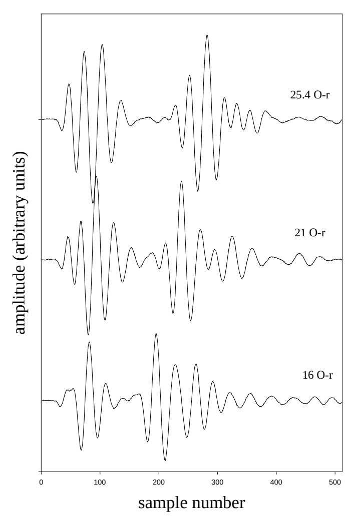


Reference: R. Kuc. Biologically-motivated adaptive sonar system. J. Acoust. Soc. America, 100(3), 1849-1854, 1996.

Rodolph – Robot dolphin

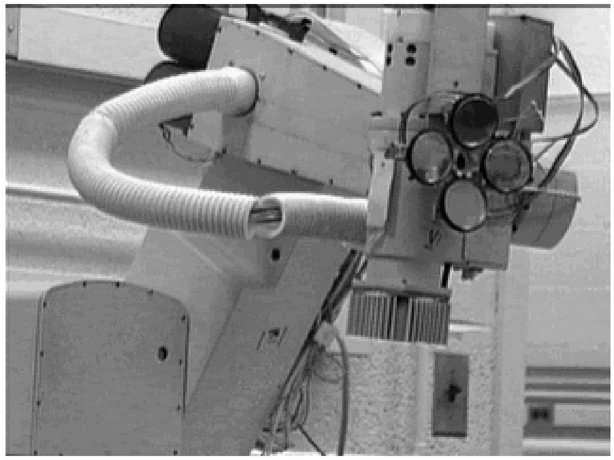


An active sonar using Polaroid electrostatic transducers positioned at the end of a robot arm is described that adaptively changes its location and configuration in response to the echoes it observes in order to recognize an object. The sonar mimics biological echo-location systems, such as those employed by bats and dolphins, in that there is a center transmitter flanked by two adjustable receivers, the sonar has full rotational and translational mobility and the echo processing contains elements that have been observed in the mammalian auditory system. Using information in the echoes, the sonar translates in a horizontal plane and rotates about vertical and horizontal axes to position an object at a standard location within the beam patterns. The transmitter points at the object to maximize the incident acoustic intensity and the receivers rotate to maximize the echo amplitude and bandwidth and to minimize the echo-producing region. The system can recognize a collection of ball bearings, machine washers and rubber O-rings of different sizes ranging from 0.45 to 2.54 cm, some differing by less than 1 mm in diameter. Recognition is accomplished by extracting 32 values from the binaural echo patterns and searching a data base. The echo waveforms from O-rings having different diameters are shown below (the numbers indicate the O-ring diameter in mm). The O-ring recognition task is analogous to that performed by dolphins using echolocation to find a hoop floating on the water. The sonar is sensitive enough to differentiate the head side from the tail side of a coin.



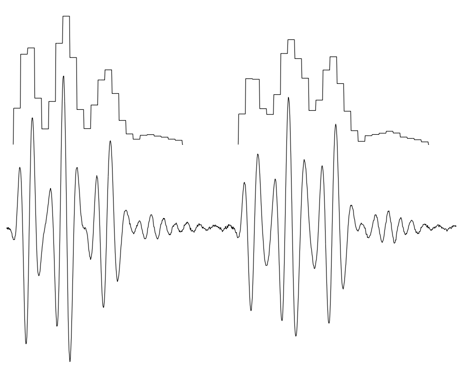
References: R. Kuc, Biomimetic sonar locates and recognizes objects. IEEE Journal of Oceanic Engineering, 22(4), 1997.

Cyclops - Sonar and camera vision system



Cyclops is a hybrid biomimetic sonar and color camera sensor system. The sensors are located at the end of an Intellidex industrial robot arm. The robot arm allows for precise movement with five degrees of movement. The sonar consists of four Polaroid instrument grade transducers (60 kHz), the two side transducers acting as receivers and the top and bottom transducers as transmitters. The Polaroid transducer has an effective beam width of 20^o. The four transducers are tilted so their axes intersect at a range of 20 cm. The top transmitter produces broad-band clicks and mimics a dolphin, whose melon transmitter lies above the ears. The bottom transmitter produces chirps from 30 to 100 kHz to mimic a bat, whose nose/mouth lie below the ears..

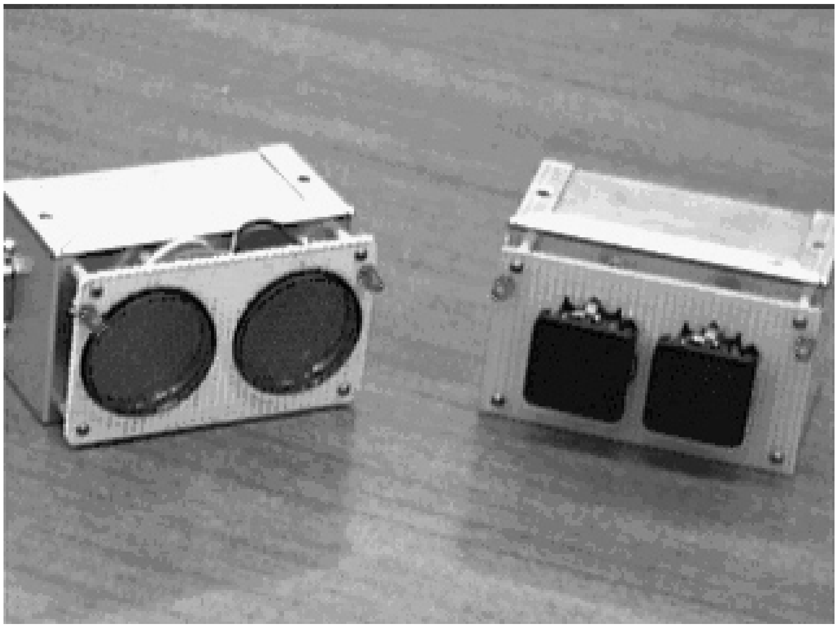
We use Cyclops for acquiring echo waveforms reflected from various deterministic and randomly-shaped objects. Deterministic objects vary from simple symmetric shapes to plastic models of animals. These are use in experiments to examine the information used by bats and dolphins to recognize prey. Echo waveforms from a pair of O-rings observed at the left and right receivers are shown below (The two waveforms have been concatenated). Feature vectors related to the envelopes are shown above the waveforms. Database formation and object recognition are based on these feature vectors.



Random shapes include coral and foliage and are used to determine how bats and dolphins recognize their environments. A computer-controlled rotating table (0.6^o increment) allows objects to be viewed in a variety of poses. A CD-ROM writer allows the data to be stored and analyzed using new algorithms.

A miniature camera points through the hole in the center of the sonar sensor. The camera has a 43^o by 33^o field of view (f6.0mm F1.6 lens) produces an image having 510 x 492 pixels. The camera image displays the structures that generate the echoes. The availability of simultaneous sonar and camera vision data allows us to investigate sensor fusion issues.

Binaural sonar provides robust bearing estimates



Time-of-flight ranging sonars are one of the most common sensors used in robotics. The chief drawback of conventional sonars is that their wide beam width prevents accurate determination of the object bearing. This problem is solved by using a pair of conventional Polaroid ranging sonars working simultaneously in a binaural configuration and by adding a simple logic circuit to determine which transducer detects the echo first. As the binaural sensor performs a rotational scan, the angle at which the shorter time-to-flight switches from one transducer to the other provides an bearing measurement that is accurate to better than 0.1^o. Its accurate bearing capability offers a solution to the occlusion of openings observed with conventional sonars (the doorway problem). The binaural sonar behavior is investigated by examining the beam patterns of simultaneously pulsed transmitters and by comparing to conventional ranging sonars.

This binaural bearing measurement is also tolerant of troublesome temperature variations in the medium, which result in poor estimates of range using time-of-flight. Since a single echo is used in the determination and the echo paths to the two adjacent transducers are nearly the same, the two time-of-flight errors are then correlated and a robust bearing estimate is obtained from their difference.

Two versions of the binaural sonar are shown above. The larger circular aperture Polaroid transducers (shown on the left) produce a stronger signal, are more sensitive receivers and exhibit narrower beam patterns. However, the 16-cycle excitation produced by the Polaroid 6500 ranging module causes side lobes in the directivity pattern. The smaller Polaroid 7000 transducers (shown on the right above) have a wider beam width and less problematic side lobes.

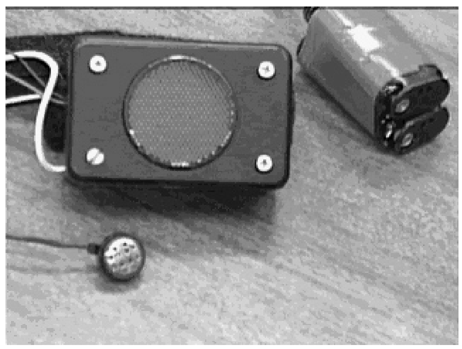
Reference: R. Kuc. Binaural sonar provides bearing measurements. Submitted to IEEE Transactions on Robotics and Automation.

Applications

Blind navigation aids

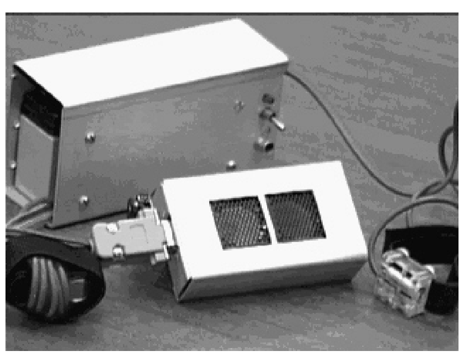
The sonar systems described above have been incorporated into two sonar navigation aids for the blind. Both use Polaroid transducers, Polaroid ranging modules and Parallax Stamp computers. Each system is powered by a single 6 V battery.

Audible feedback



This sonar uses the Polaroid instrumentation grade transducer, the 6500 ranging module and the Basic Stamp 2 computer. The stamp triggers the ranging module to transmit an interrogation pulse. The first returning echo produces a digital signal indication to the stamp. The stamp measures the time from trigger to echo arrival indication to determine the range to the nearest object. The maximum range is approximately 10 m. The stamp generates a tone pulse whose frequency increases inversely with range. That is, closer objects produce higher pitched tone pulses. The tone pulse repetition rate is also inversely related to range. That is, close objects produce quickly repeating high-pitched tone pulses, while distant objects, since they are less threatening, produce low-pitched tones that are further apart. The tone pulses are heard through an earphone.

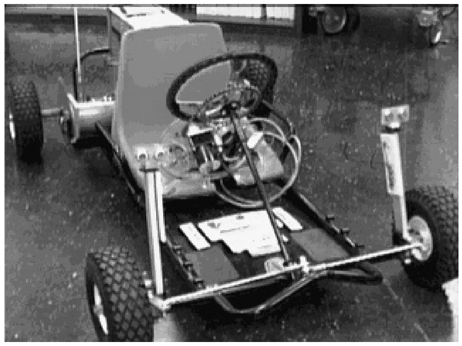
Tactile feedback



This sonar uses a pair of Polaroid 7000 transducers, a pair of 6500 ranging modules and the Basic Stamp 1 computer. The stamp triggers the ranging modules to transmit simultaneous interrogation pulses. The transducer first detecting returning echo produces a digital signal indication to the stamp. The stamp measures the time from trigger to echo arrival indication to determine the range to the nearest object. The maximum range is about 4 m. Logic in the sensor also indicates whether the right or left sensor detected the echo first, providing an indication whether the object is to the right or left of the sensor axis. The stamp energizes one of two (right or left) pager motors in one of four speeds: off (no object within 4 m), slow (object range from 2 to 4 m), fast (object range from 1 to 2 m), and very fast (object within 1 m). The pager motors are worn on the wrists.

Autonomous vehicle navigation

Yago – Yale Autonomous Go-Cart



Yago is used as a sensor test bed for a variety of sonar and electromagnetic sensors. A conventional go-cart was purchased and fitted with a pair of DC motors, one on each rear drive wheel. A stepper motor with chain drive was attached to the steering wheel. A standard mini-tower Pentium computer with 96-line digital I/O board was placed on the back, and a series of 12 V motorcycle batteries provided the power. Power for the PC was obtained from a standard 12 V to 120 VAC converter. A pair of acoustic sensors (one shown above each front wheel) determined the presence of obstacles. A scanning infrared proximity sensor determined the presence of close-by objects missed by the sonars. Yago operated autonomously by avoiding obstacles. Problems being investigated include sonar mapping and navigating through an unstructured environment. Our studies of the acoustic properties of foliage will allow us to classify and characterize plants, providing a start toward our goal of implementing an autonomous tractor for farming.

Acoustic Coupler for vehicle convoys

The problem being investigated is to acoustically couple two vehicles so that one can follow the other. Two wide-beam sonar systems, one operating at 45 kHz (rectangular aperture) and the other at 25 kHz (circular aperture), each have sufficiently narrow bandwidths such that their acoustic signals do not interfere. On each sensor the center transmitter at one frequency is flanked by two receivers at the other frequency, so the receivers on one sensor are detecting pulses from the transmitter in the other sensor. Each sensor is mounted on a stepper motor that rotates to change the azimuth. The receivers determine the corresponding transmitter bearing from the two flight times of the detected pulses. The sensor rotates to drive the bearing to zero. Upon receiving the pulses the sensor acts as a transponder and transmits a pulse at the other frequency back to the other sensor. The *sing-around* frequency is inversely proportional to range. In this way, the range and bearing of the other sensor is determined. Motor controls permit both vehicles to maintain a known separation and orientation, thus permitting turns to be executed. The stepper motor allows both sensor axes to be collinear, providing strong signals and robust operation.